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# **Resonance Control for Narrow-Bandwidth, SRF Applications**

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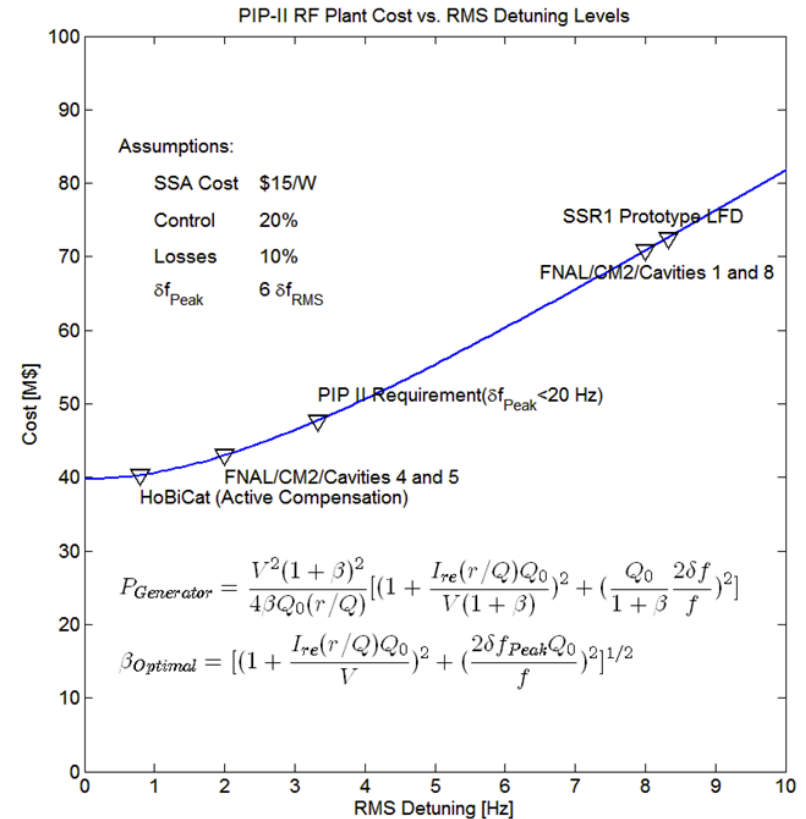
# Superconducting Cavity Detuning

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- SRF performance requires fabricating cavities from thin (2-4mm) sheets of pure niobium to allow proper cooling
  - Thin walls make cavities susceptible to detuning from vibrations
  - While some stiffening/mitigation is possible, all cavities will suffer from some detuning during operation
  - Detuned cavities require more RF power to maintain accelerating gradient
  - Providing sufficient RF reserve power to overcome cavity detuning increases both capital and operational cost of machine
- Controlling cavity detuning is critical for current generation of machines, (LCLS-II, PIP-II, ERLs, etc.) that employ very narrow bandwidth cavities
  - For machines with very narrow bandwidth cavities, e.g. ERLs, detuning can be the major cost driver for the entire machine

# RF Requirements

- Beam loading and detuning drive cost of RF systems
- Machines with lower beam loading are dominated by need to control detuning
- Critical point: *Peak Detuning drives cost*
- Peak tolerable detuning is set by the RF overhead, and this determines the machine trip rate



# Limiting Detuning

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- Passive Environmental Vibration Reduction
  - Environment around the cavity/cryomodule can contain many driving terms (cryogenics, water, vacuum, HVAC systems, etc.)
  - Passive mitigation's goal is to limit amplitude of these driving terms, reduce their transmission to the cavity system, and ensure driving terms & mechanical resonances are not aligned
  - Careful engineering during design and implementation of learned best practices will be required for new machines
- Reduce Cavity Sensitivity Through Design
  - Lorentz Force Detuning can be reduced through cavity stiffening
  - Helium bath pressure sensitivity can be mitigated through targeted stiffening
  - Mechanical resonances can be damped/shifted

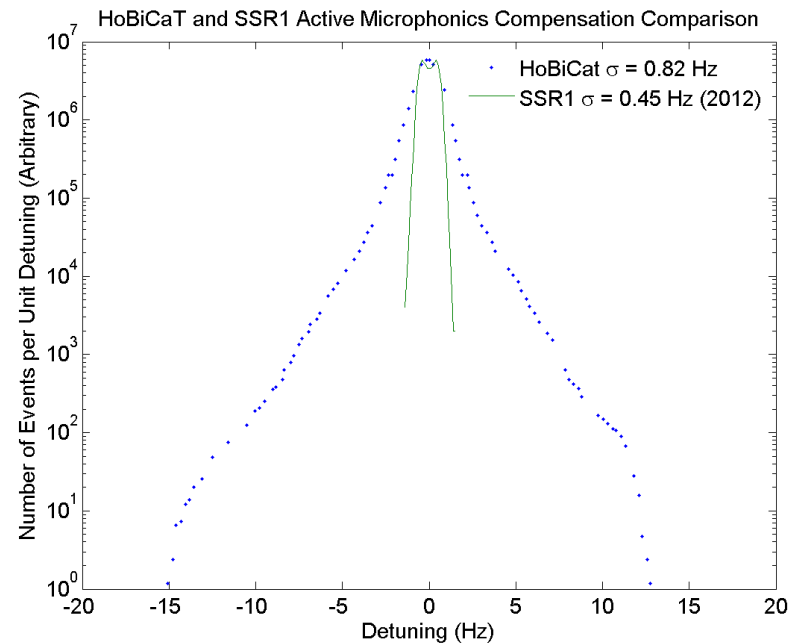
# The Last Resort – Active Compensation

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- Fast tuners (piezoelectrics) can be used to stabilize cavity resonance in presence of detuning
  - Slow, large-range motor tuners are inappropriate for any real stabilization efforts do to resolution and jarring motion
  - Piezoelectric tuners can provide the more precise, smooth, and responsive tuning needed to actively stabilize the cavity
- Detuning Sources
  - Deterministic/Feedforward Compensation
    - Lorentz Force Detuning can be compensated in proportion to the cavity stored energy
    - In pulsed mode, shot to shot correlations can be compensated
  - Non-Deterministic/Feedback Compensation
    - External Vibration/Helium Pressure drift can be calculated and compensated on the fly

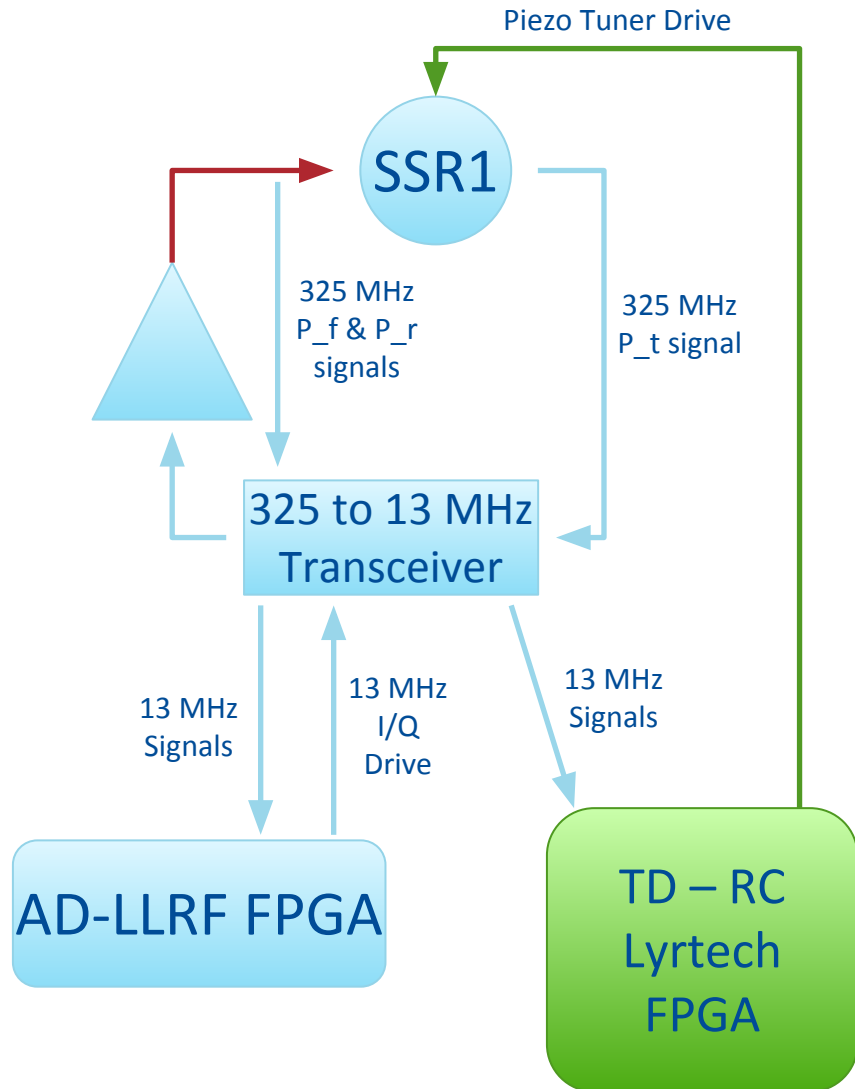
# BESSY, FNAL Achieved to Date

- Measurements at BESSY (2008) and FNAL (2012) represent the existing state of the art for CW active compensation
- BESSY data shows large tails, suspected cryo events
- FNAL-SSR1 data shows double-peak, suspected to be from different clocks running control and compensation



-HoBiCat measurements credit to Dr. Axel Neumann  
-FNAL measurements credit to Dr. Warren Schappert

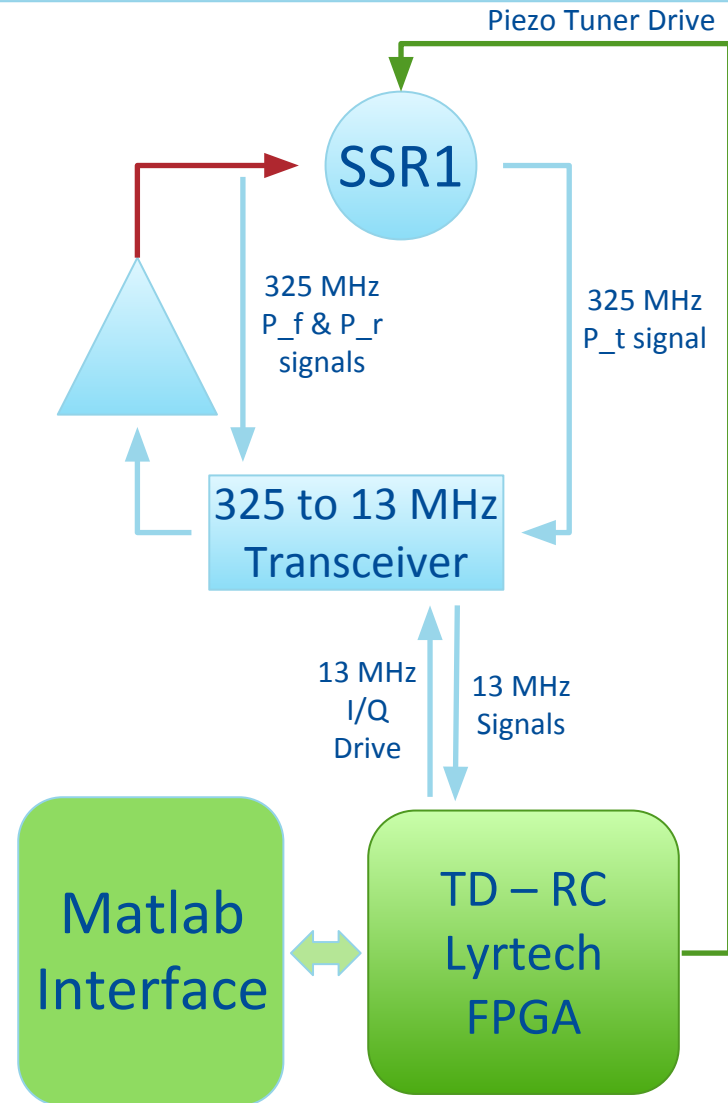
# FNAL Digital RF System



- Existing digital control system was passively monitored by the compensation system
- This was processed and used to apply compensation signal to piezo controller
- Double peaked detuning distribution suspected to be from the difference between FPGA clocks

# FNAL Digital RF System Improvement

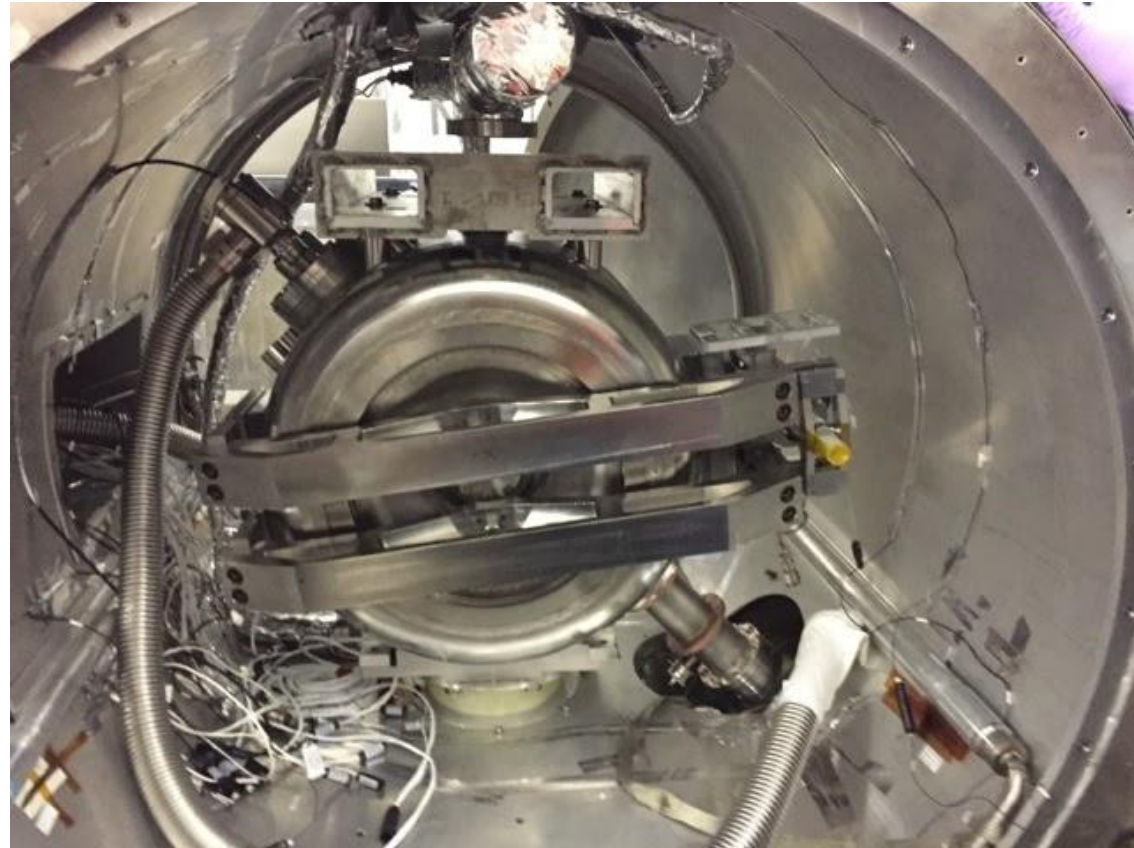
- Now, compensation system also controls cavity drive
- In the FPGA:
  - Numerically down-convert signals from 13 MHz to baseband
  - Calculate detuning
  - Output 13 MHz drive I/Q
  - Output Piezo Tuner Drive
- Common clock, common data output and recording system
- Changing transceiver allows testing at any frequency



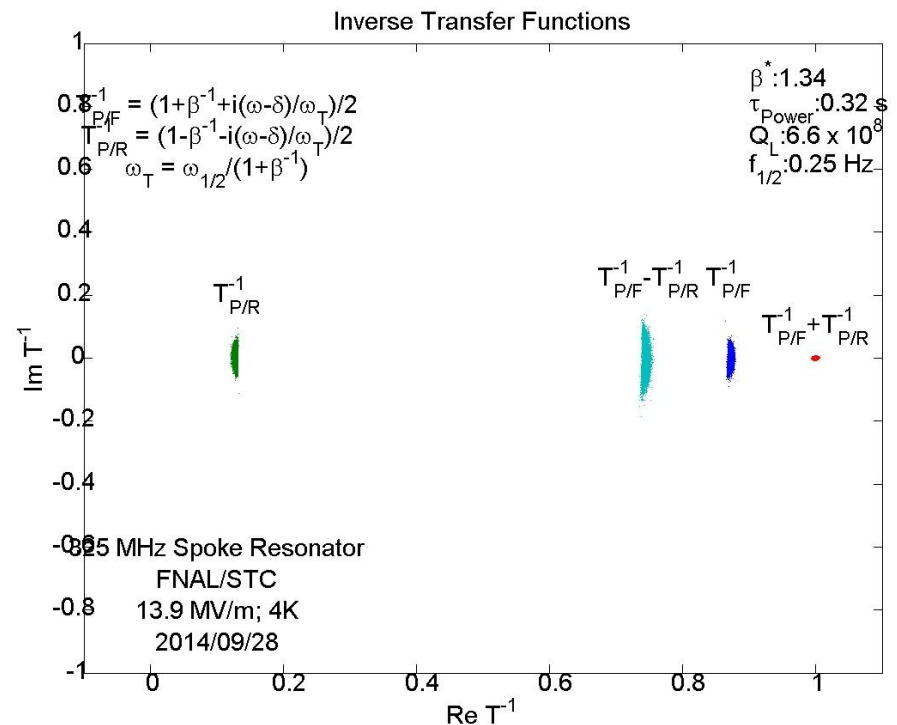
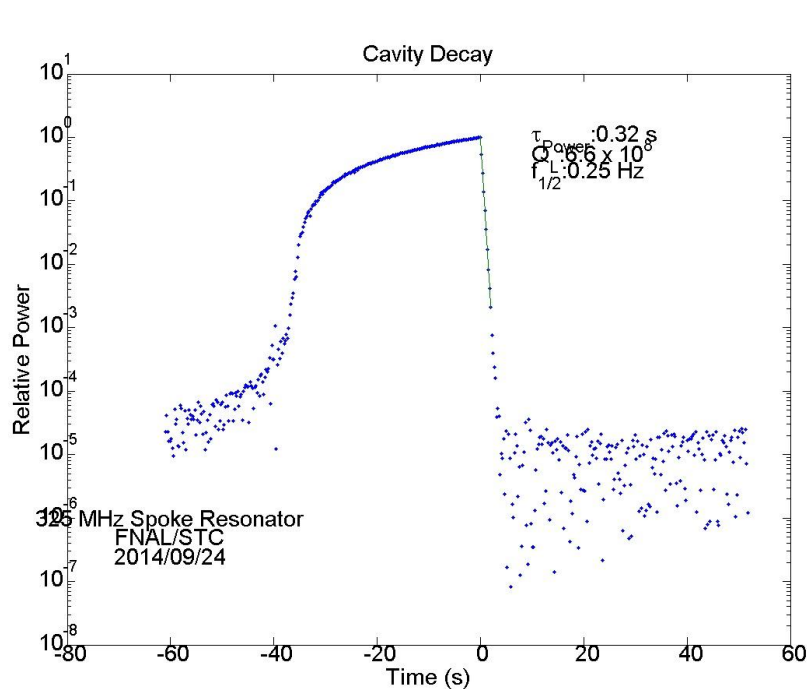


# Single Spoke Resonator for PIP-II

- 325 MHz Single-Spoke cavity designed for PIP-II project
- Near matched coupling (narrow bandwidth)
- Fixed tuner brace with no slow tuner
- Fast piezo tuner stacks in line with cavity beamline
- 4.5 K helium bath
- Tested in the Spoke Test Cryostat at FNAL



# Cavity Calibration/Characterization

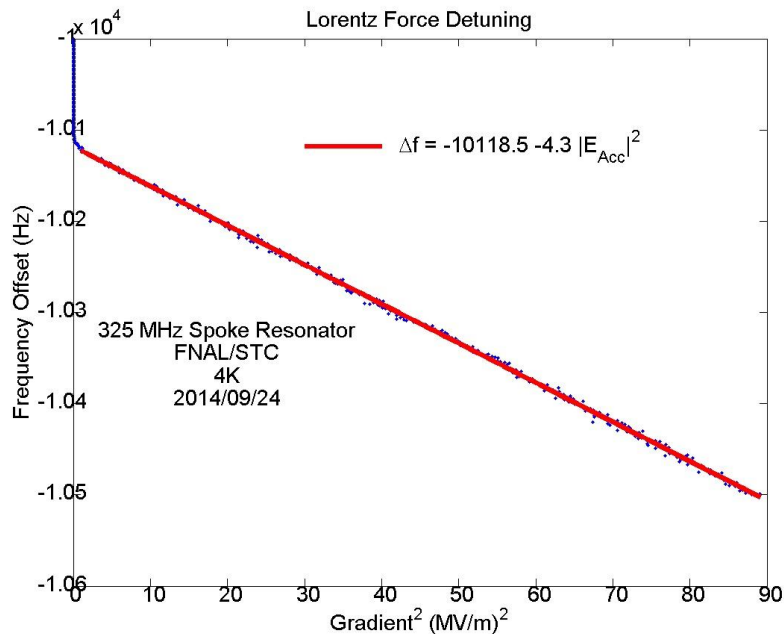


Step one is calculating cavity coupling. Loaded Q (thus bandwidth) is calculated from cavity decay time.

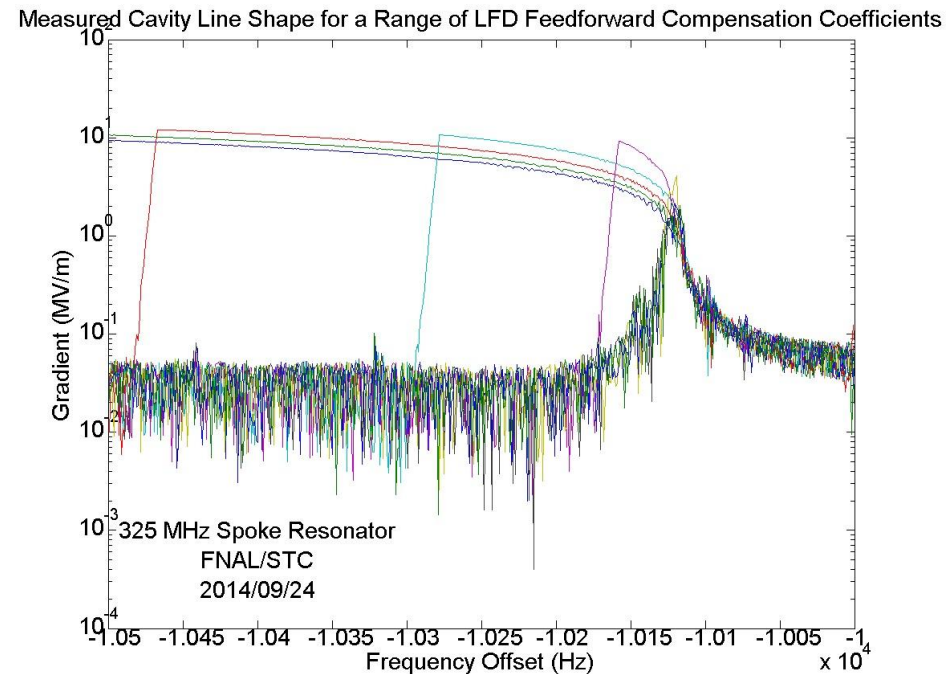
Forward/Reverse transfer functions are used to calibrate amplitude and phase using consistency conditions

See: 'Phase Method of Measuring Cavity Quality Factor' by A. Melnychuk for more details on this calibration method, WEPRI053 at IPAC2014

# Lorentz Force Detuning Feedforward Compensation

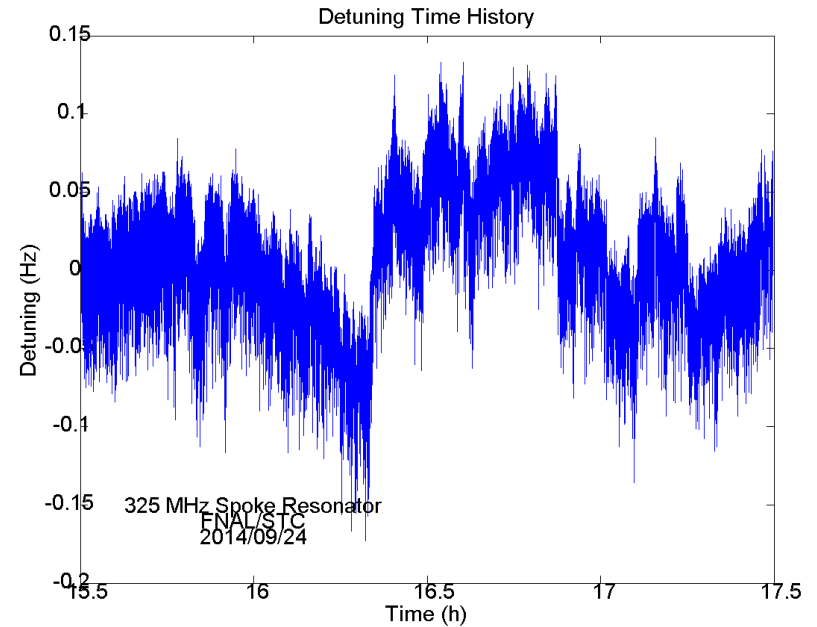
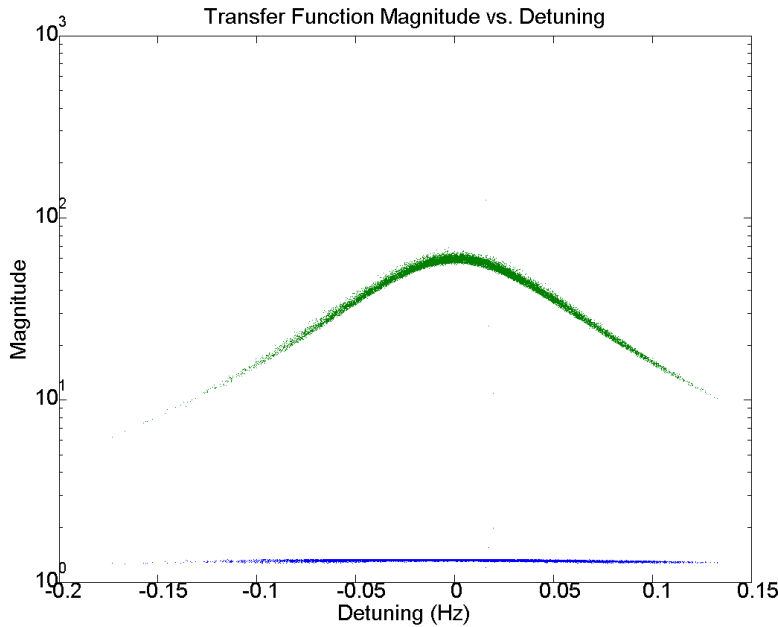


The LFD feedforward coefficient was calculated several ways, including fitting detuning during cavity decays.



The shape of the resonance curve can be seen straightening as the LFD compensation is dialed in, leading to an upright resonance.

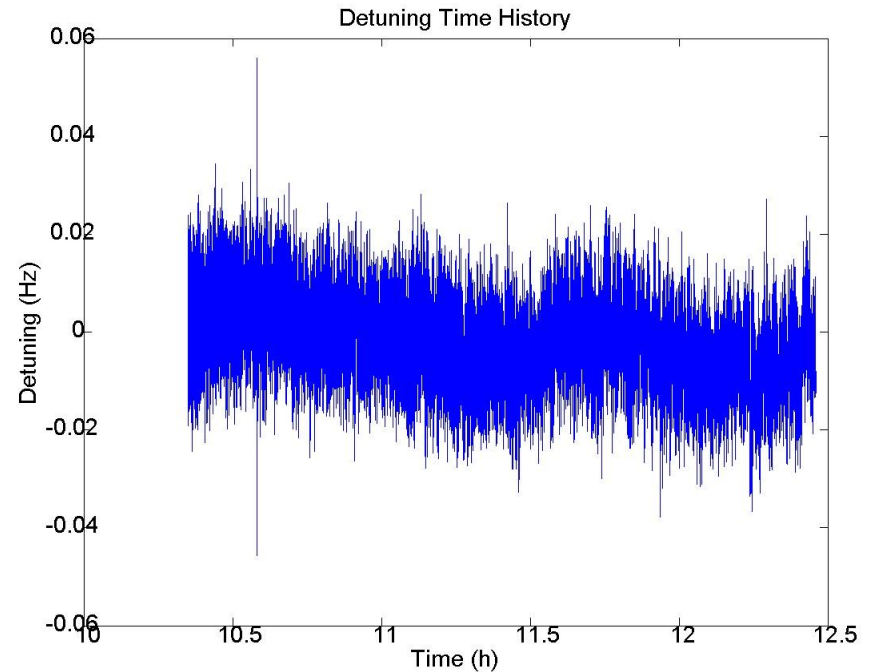
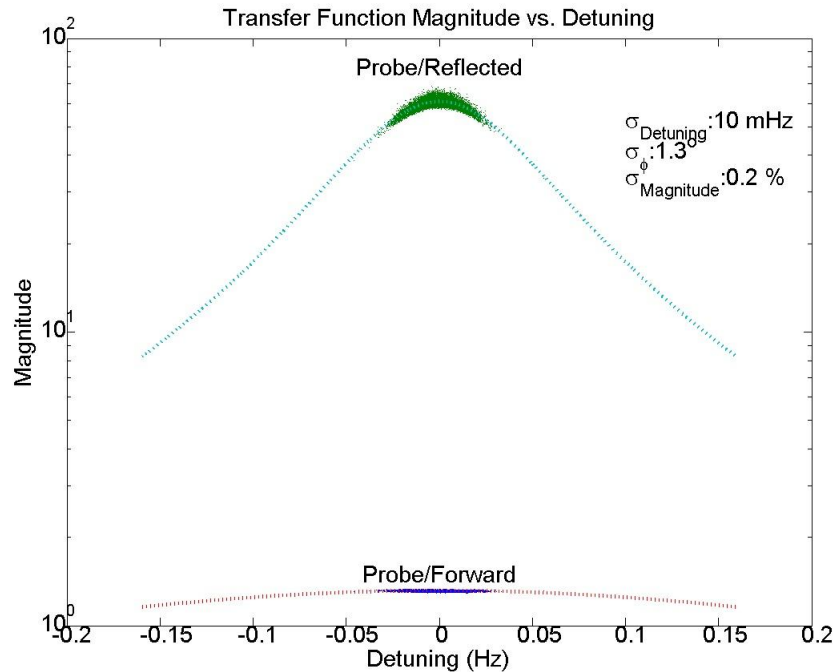
# CW Piezo Detuning Compensation



Initial efforts at direct piezo feedback of microphonics induced detuning showed good promise, but exhibited a long timescale drift.

A slow compensation loop was added in the Matlab controller to help correct for this very slow drift.

# Two Loop Compensation

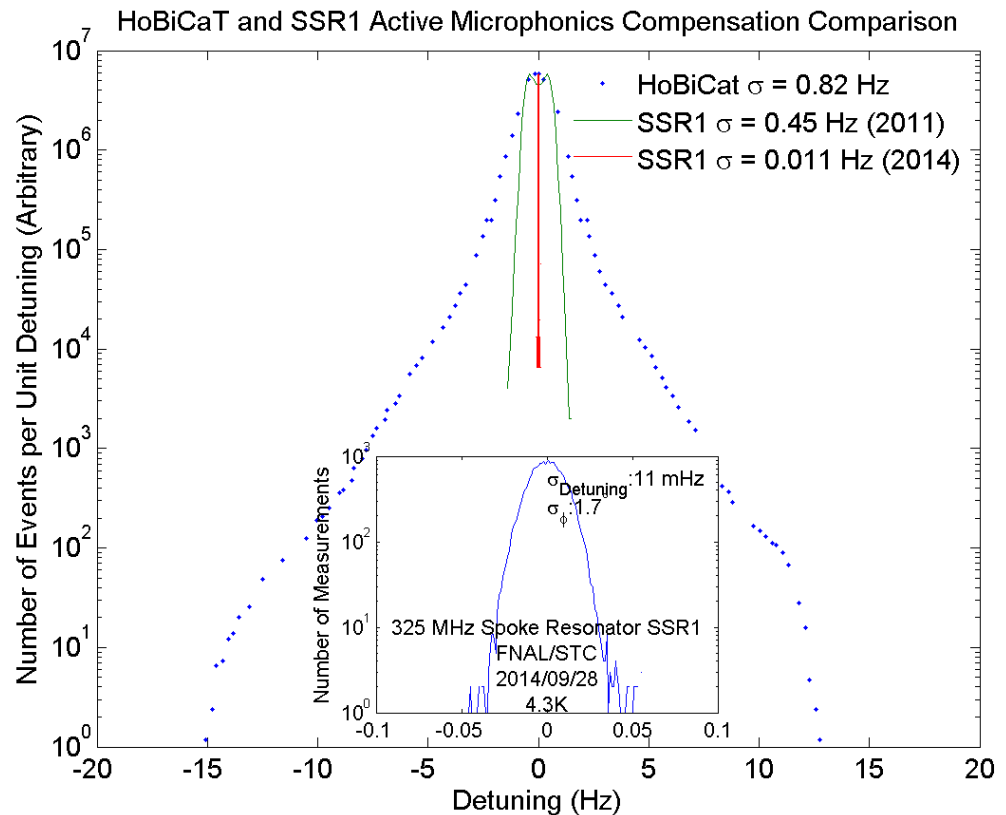


Addition of the second, slow loop improved the locking stability very nicely.

This stability is for a cavity driven open-loop, strictly stabilized by feedforward and feedback loops with piezo tuner.

# Best Results at FNAL

- New control system seems to have removed the double-peak seen in the 2011 FNAL data.
- Measurement conditions:
  - Open loop drive
  - 4.3 K
  - 0.25 Hz Bandwidth
  - 5.8 Peak/RMS
  - 325 MHz Single Spoke Resonator
  - 2 hours of data
  - Fast feedback loop
  - Slow feedback loop
  - LFD feedforward
  - 11 mHz RMS detuning
  - 14 MV/m Gradient
  - 1.3 degrees RMS phase
  - 0.02% RMS amplitude



# Conclusions

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- Controlling cavity detuning will be critical for successful operation of PIP-II because of narrow cavity bandwidths ( $f_{1/2} \sim 30$  Hz)
  - Narrow bandwidths would be challenging even with CW operation alone
  - Pulsed mode operation brings significant additional complications
- All possible passive measures must be exploited but active control will still be required
  - Will require both best LFD and best microphonics compensation achieved to date operating reliably over many cavities and many years
    - Early test results provide reason for **CAUTIOUS** optimism
  - There are no existing examples of large machines that require active control of detuning during routine operation
- Cross-disciplinary challenges may be more difficult to solve than technical challenges (which are still considerable)
  - Minimizing cavity detuning requires optimization of entire machine
  - Will require active coordination across divisions and across disciplines



## Current Work and Future Plans

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- We are currently working with improved SSR1 cavity for PIP-II and prototype 1.3 GHz cavities for LCLS-II at FNAL's Spoke Test Cryostat (STC) and Horizontal Test Stand (HTS)
- Various parts of the detuning calculation, implementation, and functionality of the FPGA code are currently being commissioned
- CW work continues for LCLS-II, and work with pulsed-mode operation has started for PIP-II
- Current plan is to implement the adaptive algorithm for LFD compensation developed for ILC cavities at FNAL
- From there, more advanced algorithm work is planned to integrate detuning, amplitude, and phase stability using a Kalman Filter



# Questions?

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- Special acknowledgements to Y. Yakovlev and Y. Pischalnikov for supporting this work at FNAL
- Work presented on behalf of the Technical Division - Resonance Control Group
- Thanks for your attention!